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ABSTRACT

If the weak bosons $W^{\pm}$ and Z were manifestations of a composite structure of the weak interactions rather than the commonly assumed gauge bosons of a fundamental gauge symmetry one is naturally led to expect a corresponding spectrum of other new weak vector bosons such as weak isoscalars. Experiments at the LHC are of great value in establishing the true nature of the weak interactions.

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ISOSCALAR WEAK VECTOR BOSONS AT THE LHC

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Abstract

If the weak bosons $W^{\pm}$ and Z were manifestations of a composite structure of the weak interactions rather than the commonly assumed gauge bosons of a fundamental gauge symmetry one is naturally led to expect a corresponding spectrum of other new weak vector bosons such as weak isoscalars. Experiments at the LHC are of great value in establishing the true nature of the weak interactions.

The Glashow-Weinberg-Salam model [1] constitutes a first coherent picture of electroweak interactions and the discovery of the $W^{\pm}$ and Z bosons at the CERN $p\bar{p}$ collider [2] have greatly strengthened the belief that this model may be a true description of the electroweak phenomena. However, important features of the standard picture are completely untested by experiment so far – just think of the open question of the self-couplings of the gauge bosons or of the Higgs sector. For future testing of the standard picture it is therefore of greatest importance to consider realistic alternatives and clearly isolate the standard predictions among the multitude of other models. A composite structure of the weak interactions [3] is an attractive alternative where it is most natural that one predicts new isoscalar partners $Y(Y_L)$ of the isovector $W^{\pm}$ and Z bosons [4, 5] which are either coupled to the weak hypercharge current, or its lefthanded part.

In the following we will discuss the impact of $Y(Y_L)$ on experiments at the LHC [6]. The weak isospin $SU(2)_{WI}$ symmetry is taken to be a global symmetry of the underlying preon model in the limit of a vanishing electromagnetic coupling constant $e = \sqrt{4\pi\alpha}$. In addition in this limit there is a global $U(1)$ invariance related to the weak hypercharge. One can imagine this symmetry to be either active in the left-handed sector only ($y_L = Q - T_3$) similar to the isospin symmetry (case with a Y_L-boson) or in the right- and left-handed (y_L as above, $y_R = Q$) sector (case with a Y-boson). For $\alpha \neq 0$ all this is modified by the mixing of the $Y(Y_L)$ and the isovector W^3 with the photon [5]. The couplings obtained by saturating the electromagnetic form factors by massive vector bosons (W^3- and $Y(Y_L)$-dominance [5]) and after performing a diagonalization to mass eigenstates are summarized in the appendix. They have some interesting properties especially

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for the Y_L where the vector and axial vector coupling constants $V_{Y_{(L)}}$ and $A_{Y_{(L)}}$ (see Eqs. (A11) and (A12) in the appendix) exhibit a strong sensitivity to the $\gamma Y_{(L)}$ mixing parameter λ_Y [7] which is related to the γW^3 mixing strength $\lambda_W \approx \sin\theta_W$ and the $W(Y_{(L)})f\bar{f}$-fermion coupling constant $g_{W(Y)}$ by $g_W\lambda_W = g_Y\lambda_Y = e$. One finds:

a) For small values of λ_Y^2 (corresponding to a large g_Y) the couplings are almost exclusively such as if there were no mixing with the photon, hence $V_Y \approx (e/\lambda_Y)\ (2Q - T_3)$, $A_Y \approx (e/\lambda_Y)\ T_3$ and $V_{Y_L} \approx\ -A_{Y_L} \approx (e/\lambda_Y)\ (Q - T_3)$.

b) For large values of λ_Y^2 (corresponding to a small g_Y) the Y behaves distinctly different from the Y_L. The Y couplings get very small which leads to an almost decoupling from the fermions in this limit. The Y_L couplings, however, are not small and Y_L couples practically in a purely right-handed way to the fermions carrying electric charge.

c) The region of intermediate λ_Y^2 is characterized by a set of zeros in the vector and axial vector couplings of the Y_L whereas the Y couplings smoothly interpolate between the values of a) and b). The vector coupling V_{Y_L} disappears for leptons when (M_Y: $Y(Y_L)$-mass; m_W: W-mass)

$$\lambda_Y^2(V_{Y_L} = 0, \ell^\pm) \ = \ \frac{(1-\lambda_W^2)M_Y^2 - m_W^2}{3M_Y^2 - 4m_W^2} \ \approx\ 0.263 - 0.264 \ , \tag{1}$$

for up-type quarks U when

$$\lambda_Y^2(V_{Y_L} = 0, U) \ = \ \frac{(1-\lambda_W^2)M_Y^2 - m_W^2}{5M_Y^2 - 8m_W^2} \ \approx\ 0.158 - 0.162 \ , \tag{2}$$

and the axial coupling A_{Y_L} does so for down-type quarks D at

$$\lambda_Y^2(A_{Y_L} = 0, D) \ = \ \frac{1}{3}(1-\lambda_W^2) - \frac{1}{3}\frac{m_W^2}{M_Y^2} \ \approx\ 0.238 - 0.263 \ . \tag{3}$$

This pattern of couplings can be easily found again in the dependence of production cross sections etc. on the parameter λ_Y^2. We should shortly dwell on the decay properties of the Y and Y_L. Naturally one has all the possible decays into fermion-antifermion pairs with strengths reflecting the various couplings. It seems especially notable that compared to Z decays in this case the e^+e^- mode has a quite large branching ratio $B(e^+e^-)$ of roughly 12 % for the Y_L throughout the whole permissable range and for the Y for most of it ($\lambda_Y^2 \leq 0.5$) dropping sharply towards bigger λ_Y^2 values. This property will facilitate discovery in hadron colliders. Through the mixing of photon and $Y(Y_L)$ and W^3 respectively the decay channel $Y(Y_L) \to W^+W^-$ opens up [7] whose strength increases for the Y for values of $\lambda_Y^2 > 0.5$ whereas the Y_L has only a small branching ratio into W^+W^- for all λ_Y^2 (roughly $1-2$ %).

In discussing the production cross sections we use the narrow width Drell-Yan approximation with [8]

$$\sigma(Y(Y_L)) = \frac{4}{3}\frac{\pi^2}{M_Y^3}\left(\sum_{a,b}\Gamma(Y(Y_L) \to ab)\tau\frac{d\mathcal{L}_{ab}}{d\tau}\right) \tag{4}$$

where $\tau = M_Y^2/s$, $d\mathcal{L}_{ab}/d\tau$ is the parton luminosity and a, b are the parton species.

Folding in the branching ratio $B(e^+e^-)$ we compare in Fig. 1 $\sigma \cdot B(e^+e^-)$ at a) constant $\lambda_Y^2 = 0.2$ and varying mass M_Y and b) constant mass $M_Y = 500\ GeV$ and varying λ_Y^2 for the LHC collider and the now operational Tevatron facility using the parton densities set 1 of ref. [9]. Other combinations of M_Y and λ_Y^2 produce similar but shifted curves. One finds that for the LHC $\sigma \cdot B(e^+e^-)$ is larger than 1 pb for a wide range of M_Y ($\leq 0.8\ TeV$) and λ_Y^2 (≤ 0.5). This bodes well for a discovery of such a particle at the LHC and only the question about background remains. This question can be settled conclusively by remarking that the Drell-Yan e^+e^- background is roughly a factor 10^3 smaller and dileptons from $b\bar{b}$ production are about a factor 10^2 below the signal [7] . One should note that the trough-like shape of the Y_L curve in Fig. 1b) reflects the zeros in V_{Y_L} and A_{Y_L} of the charged fermions while for the Y the decoupling for large λ_Y^2 is clearly reflected.

The $V's$ and $A's$ influence yet another quantity, namely the forward-backward asymmetry $A_{FB}(y)$ of the emitted leptons in the boson rest frame [10] :

$$A_{FB}(y) = \frac{F(y) - B(y)}{F(y) + B(y)} \tag{5}$$

with

$$F(y) \pm B(y) = \left[\int_0^1 \pm \int_{-1}^0\right] dz\ \frac{d^2\sigma(q\bar{q} \to Y(Y_L) + X \to \ell^+\ell^- + X)}{dy\ dz} \tag{6}$$

where y is the $Y(Y_L)$ rapidity and z is the cosine of the angle between lepton and beam direction in the $Y(Y_L)$ rest frame. For the LHC (pp) $A_{FB}(y)$ is antisymmetric with respect to $y = 0$ whereas it would be symmetric for the Tevatron ($p\bar{p}$). The asymmetry for the Y is almost independent of λ_Y^2 rising to values ± 0.4 at $y = \pm y_{max} = \pm \ln(\sqrt{s}/M_Y)$, for very large $\lambda_Y^2 > 0.5$, however, it becomes smaller. The Y_L asymmetry on the other hand is distinctly different. It is large at small λ_Y^2 due to the almost purely left-handed coupling and becomes small and of opposite sign for intermediate λ_Y^2 (~ 0.2) reflecting the zeros in the charged fermion couplings. At large λ_Y^2 we again obtain big asymmetries because of the now almost right-handed couplings of Y_L. Thus it may be difficult to separate a Y_L of small mixing from such with large mixing parameter in $A_{FB}(y)$.

Finally, we mention the production of $Y(Y_L)$ in the W^+W^- channel. Since the $Y_{(L)}WW$ coupling is purely induced by $\gamma Y_{(L)}$ mixing [7] it is only relevant for larger λ_Y^2 values (≥ 0.30) and even there suffers from the considerable $q\bar{q} \rightarrow W^+W^-$ standard model background and from a large hadronic background which complicates the identification of W-pairs at hadron colliders [11]

.

Summarizing we want to give a strategy for identifying Y- or Y_L-bosons at the LHC. First of all, we should expect to see a "bump" in the e^+e^- invariant mass distribution signalling their existence. As such a "bump" would be non-specific – it could be any Z' or Y^* of strange other quantum numbers, maybe, originating from all sorts of new physics like superstrings – it is desirable to perform an analysis of the asymmetry $A_{FB}(y)$ and of the W^+W^- channel which could allow further information on the mixing parameter λ_Y^2 in such a way that our model would be totally specified. At the proposed LHC it should be possible to carry out such a program for $Y(Y_L)$-masses up to 1 TeV which includes the range expected for such particles. For comparison the Tevatron can only detect an isoscalar boson of mass smaller than 400 GeV in which region, however, one would hardly expect them to lie anyway on account of present low energy neutral current data [12] . Thus the LHC is well suited to identify a possible deviation from our GWS picture of the electroweak interactions.

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APPENDIX

Here we list the effective Lagrangian for the interactions of $Y(Y_L)$- and Z-bosons with fermion and W-boson pairs after performing the diagonalization to mass eigenstates [12] . W^3- and $Y(Y_L)$-dominance is applied to the vector boson fermion coupling as well as to the self-interactions of W, Z and $Y(Y_L)$.

In presence of an isoscalar vector boson Y or Y_L the effective Lagrangian for $Zf\bar{f}$ interactions is given by [12]

$$\mathcal{L}_{Zf\bar{f}} = Z_\mu \left[\sum_f \bar{f}\gamma^\mu \frac{1}{2}(V_Z^{Y(L)} + A_Z^{Y(L)}\gamma_5)f\right] \tag{A1}$$

where in the Y-case

$$A_Z^Y = \frac{e}{b_Z} \frac{M_Z^2}{M_Z^2 - m_W^2} \frac{m_Y^2 - m_W^2}{M_Z^2 - m_Y^2} T_3 , \qquad (A2)$$

$$V_Z^Y = 2\frac{e}{b_Z} \frac{m_Y^2}{M_Z^2 - m_Y^2} Q - A_Z^Y \qquad (A3)$$

and in the Y_L-case

$$A_Z^{Y_L} = -\frac{e}{b_Z} \frac{M_Z^2}{M_Z^2 - m_Y^2} Q + A_Z^Y , \qquad (A4)$$

$$V_Z^{Y_L} = -\frac{e}{b_Z} (1 - \frac{m_Y^2}{M_Z^2 - m_Y^2})Q - A_Z^Y . \qquad (A5)$$

Q and T_3 are the electric charge and the third component of the weak isospin, repectively; m_W is the W-mass and b_Z, M_Z and m_Y are given below.

The ZWW interaction Lagrangian is [13] $(V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu;\ V = W, Z, Y_{(L)})$

$$\mathcal{L}_{ZWW} = -ig_{ZWW} \left[Z^{\mu\nu} W_\mu^+ W_\nu^- - Z^\nu \ (W^{+\mu} W_{\mu\nu}^- - W^{-\mu} W_{\mu\nu}^+)\right] \qquad (A6)$$

with

$$g_{ZWW} = -\frac{e}{b_Z} \frac{m_W^2}{m_W^2 - M_Z^2} . \qquad (A7)$$

For the effective Lagrangian describing $Y(Y_L)f\bar{f}$ interactions one obtains [7]

$$\mathcal{L}_{Y_{(L)}f\bar{f}} = Y_{(L)\mu} \left[\sum_f \bar{f}\gamma^\mu \frac{1}{2}(V_{Y_{(L)}} + A_{Y_{(L)}}\gamma_5) f\right] . \qquad (A8)$$

The vector and axial vector coupling constants $V_{Y_{(L)}}$ and $A_{Y_{(L)}}$ of Y and Y_L are

$$A_Y = \frac{e}{b_Y} \frac{M_Y^2}{M_Y^2 - m_Y^2} \frac{m_Y^2 - m_W^2}{M_Y^2 - m_W^2} T_3 , \qquad (A9)$$

$$V_Y = 2\frac{e}{b_Y} \frac{m_Y^2}{M_Y^2 - m_Y^2} Q - A_Y \qquad (A10)$$

and

$$A_{Y_L} = -\frac{e}{b_Y} \frac{M_Y^2}{M_Y^2 - m_Y^2} Q + A_Y , \qquad (A11)$$

$$V_{Y_L} = -\frac{e}{b_Y} (1 - \frac{m_Y^2}{M_Y^2 - m_Y^2})Q - A_Y . \qquad (A12)$$

M_Y is the $Y(Y_L)$-mass and b_Y is given in Eq. (A19).

Finally, the $Y(Y_L)WW$ interaction Lagrangian reads [7]

$$\mathcal{L}_{Y_{(L)}WW} = -ig_{Y_{(L)}WW}\left[Y_{(L)}^{\mu\nu}W_\mu^+W_\nu^- - Y_{(L)}^\nu(W^{+\mu}W_{\mu\nu}^- - W^{-\mu}W_{\mu\nu}^+)\right] \tag{A13}$$

with

$$g_{Y_{(L)}WW} = -\frac{e}{b_Y}\,\frac{m_W^2}{m_W^2 - M_Y^2}\,. \tag{A14}$$

Since the self-interactions of W, Z and $Y(Y_L)$ are, in the limit of vanishing $\gamma Y_{(L)}$ mixing, of massive Yang-Mills type if W^3- and $Y(Y_L)$-dominance is applied, $g_{Y_{(L)}WW} \to 0$ for $\lambda_Y \to 0$.

The Z-mass M_Z is given by [7]

$$M_Z^2 = \frac{m_W^2}{1-\lambda_W^2-\lambda_Y^2}\,\frac{m_Y^2}{M_Y^2} \tag{A15}$$

where

$$\lambda_W^2 = \frac{e^2}{m_W^2}\,\frac{\sqrt{2}}{8}\,G_F^{-1} \tag{A16}$$

plays the role of $\sin^2\theta_W$ and

$$m_Y^2 = M_Y^2\,\left(1 - \lambda_Y^2\,\frac{M_Y^2 - m_W^2}{(1-\lambda_W^2)M_Y^2 - m_W^2}\right) \tag{A17}$$

is the unobservable "bare" mass of the $Y(Y_L)$-boson. Since $m_Y^2 \geq 0$, the $\gamma Y_{(L)}$ mixing strength λ_Y^2 is bounded from above by

$$\lambda_Y^2 \leq 1 - \lambda_W^2\,\frac{M_Y^2}{M_Y^2 - m_W^2} < 1 - \lambda_W^2 \approx 0.77\,. \tag{A18}$$

The coefficients $b_i,\ i = Z, Y$ are

$$b_i^2 = 1 - \lambda_W^2 - \lambda_Y^2 + \lambda_W^2\,\frac{m_W^4}{(m_W^2 - M_i^2)^2} + \lambda_Y^2\,\frac{m_Y^4}{(m_Y^2 - M_i^2)^2}\,. \tag{A19}$$

For $\lambda_Y^2 \to 0$ and $M_Y \to \infty$ the Z-boson mass and coupling constants approach their standard model values. For a more detailed discussion of the couplings of Z and $Y(Y_L)$ to fermions and W-bosons we refer the reader to refs. [7], [12] and [13].

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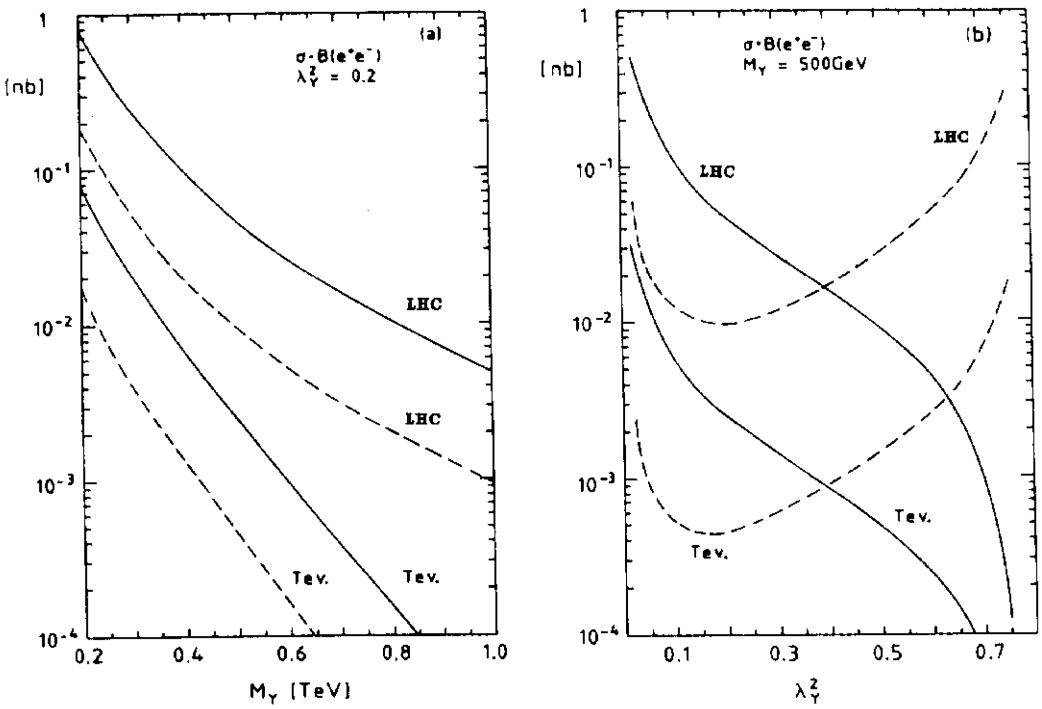

Fig. 1: The production cross section times leptonic branching ratio, $\sigma \cdot B(e^+e^-)$

a) versus M_Y for $\lambda_Y^2 = 0.2$

b) versus λ_Y^2 for $M_Y = 500\ GeV$.

The curves are given for the LHC pp and the Tevatron $p\bar{p}$ version (denoted by "Tev.") for comparison respectively. Solid (dashed) lines correspond to $Y(Y_L)$.